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Energy and exergy analyses of solar-assisted fluidized bed drying integrated with biomass furnace

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ABSTRACT

A hybrid solar-biomass fluidized bed drying system was designed, evaluated and developed. The system was comprised of a fluidized bed, a solar collector, and a biomass furnace. This solar-assisted fluidized bed dryer integrated biomass furnace was used to investigated the drying kinetics of paddy. The average temperature of the air drying were 61 and 78 °C. The paddy's moisture content was dried to 14% from 20% (wet basis) with a mass flow rate of 0.125 kg/s. The performance of the fluidized bed drying system was assessed base on energy and exergy analyses. The specific energy consumption (SEC), solar fractions, biomass fractions, thermal and exergy efficiencies were obtained. The SEC and drying times were lower in hybrid solar-biomass fluidized bed drying system compared to solar dryers.

1. Introduction

Recently, fossil fuels have been the main primary energy in the worldwide. However a series of serious problems have occurred due to over utilization of fossil fuels, such as climate change, CO_2 emission, and ecological balance disruption. Therefore, various renewable energy resources are drawn increased attention for their environmental advantages, especially solar energy and biomass energy, have been widely used as a result of their unique advantages, such as cleanliness, abundant reserves, safety and so on [1]. Solar drying was used to dry agricultural products especially in tropical and subtropical countries. It is one of the most efficient solar energy applications because its energy is free, renewable, and abundant. Traditional sun drying has been used since time immemorial to dry agricultural products, where the product is exposed directly under the sun. However, it has many disadvantages, such as degradation by wind-blown debris, rain, insect infestation, and human and animal interference, which result in low-quality products and long drying times. The solar drying system provides an alternative for traditional sun drying to dry agricultural products [2–4].

Recently, various solar drying systems with air and water-based solar collectors were reported [5,6]. Many studies have been reported on solar drying systems for agricultural and marine products, such as seaweed [7], palm oil fronds [8], red chili [9,10], green peas [11], cassava [12], banana [13], and herbs and spices [14]. However, the drying process cannot be achieved during cloudy and rainy days, and during night time because of lack of sunlight. The problems in solar dryers can be resolved by the use of a biomass backup heater. Several studies have been reported on solar dryers with biomass backup heater for drying agricultural products, such as coconut [15], maize grain [16], banana [17], herb, pineapple [18], and *Zingiber officinale* [19].

In Indonesia, paddy is the staple food of nearly 90% of the population and an economic resource of more than 30 million farmers. Indonesia is the third biggest paddy-producing country worldwide with its annual production of around 78 million ton [20]. Paddy after harvest generally have high moisture content of about 20–23% wet basis in the dry season and about 24–27% wet basis in the wet season [21]. Therefore, to secure long-term storage paddy needs to be dried as soon as possible to achieve moisture content of about 14% wet basis [22]. Commonly, paddy is dried using traditional sun drying.

There are many drying systems for different processes, including

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solar, fluidized bed, heat pump, and several other processes. Fluidized bed dryers can be used to dry paddies to resolve the disadvantages of the traditional sun drying. Among various hot air drying methods, fluidized bed dryer offers significant advantages such as high drying rate and uniform moisture reduction with less drying time. Fluidized bed drying also high heat and mass transfer rates, which can be attributed by the good contact between the particles and drying gas, uniform temperature, and bulk moisture content of particles; these effects are caused by intensive particle mixing in the bed, closely controllable temperature in the bed, ease in transport and handling of particles, simplicity in construction, and high-drying capacity because of high ratio of air mass to product mass [23,24]. Fluidized bed dryers have been used to dry agricultural products such as brown rice [25], corn [26], carrots [27], chili [28], green peas [29], celery [30], and apple [31]. Fluidized bed dryers commonly were used in processing various products, such as agrochemicals, beverages, biomaterials, carbohydrates, ceramics, chemicals, detergents, fertilizers, food, pesticides, pigments, polymers, powder, resins, tannins, etc [32].

Biomass is the plant material derived from the photosynthesis between sunlight, CO_2, and water to produce carbohydrates, thus it is carbon–neutral resource and renewable. Biomass has some other advantages such as abundant in resources, widely distributed, environmental friendly. One of the most potential technologies of biomass utilization is gasification [1]. Using gasification technology, a solid fuel such as plastics or biomass is transformed to the product gas with various uses like district heating, chemical syntheses and the electricity production in gas engines [33].

Many studies have been reported on fluidized bed dryers for drying paddy [34–41]. However, to our knowledge, information is limited on literature about the drying behavior of paddies in solar-assisted fluidized bed dryers integrated with biomass furnace. Therefore, the purpose of this paper is to design and evaluate the performance of solar-assisted fluidized bed dryers integrated with biomass furnace for drying of paddies in Indonesia. In this study, performances analyses were conducted base on energy and exergy analyses.

Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment. Also, exergy analysis is a useful method to establish strategies for the design and operation of many industrial processes where the optimal use of energy is considered an important issue. This information is effective in determining the plant and the operation cost, the energy conservation, the fuel versatility and the pollutant. In the recent years, exergy analysis has been widely used for the performance evaluation of thermal systems. In the drying process, the aim is to uses minimum amount of energy for maximum moisture removal for the desired final conditions of the products [42–44].

2. Material and methods

The photographs and schematics diagram of the fluidized bed dryer integrated with biomass furnace are shown in Figs. 1 and 2. The drying system consists of the following main components: solar collector array, biomass furnace, fluidized bed, cyclones, and blowers. The solar collector consists of several main parts: transparent cover glass material, absorbent plate finned using aluminum and black-painted opaque, angle iron frame, the inside and outside of the collector coated with 1 mm thick aluminum, and insulation using glass fiber materials. Two solar collectors connected in series with an area of 1.8 m^2 each. For dimensions of a single-pass solar collector with fin as shown in a solar-assisted previously described by Yahya [45].

Biomass furnace consists of several main parts such as the combustion chamber, heat exchanger, chimney, and blower. The wall of the combustion chamber uses brick, cement and steel plate materials, and heat exchanger pipes using mild steel with diameter of 0.051 m and number of pipes is 16 unit, which dimensional of biomass furnace as shown in a solar-assisted previously described by Yahya [45]. The fluidized bed consists of a drying chamber, air flow distribution, and an inlet and exit of rice; the front part of the drying column is covered with clear glass 0.005 m thick; the sides and back are covered with 0.003 m -thick aluminum plate, while the air distributor uses wire aluminum gauze; the dimensions are shown in Fig. 2b. The cyclone is covered with an aluminum plate 0.003 m thick, and its dimensions are shown in Fig. 2c. The blower uses centrifugal type with 3.7 kW power, and two blowers with 150 W powers.

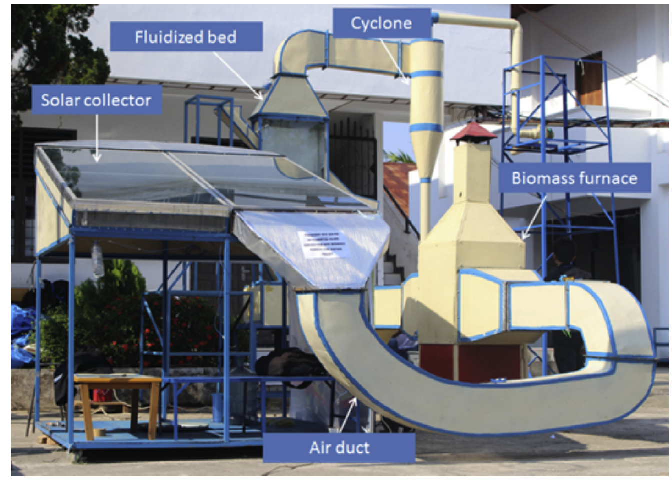

Fig. 1. Photograph of the solar assisted fluidized bed dryer integrated with biomass furnace.

The experiments are conducted at Institut Teknologi Padang, West Sumatra, Indonesia. Fresh paddies (*Oryza sativa* L.) were purchased from a farmer in Padang, and as much as 12 kg were placed in the drying column for the drying process. Biomass fuels use coconut shell charcoal. Incoming and outgoing air temperature of the biomass furnace and drying column are measured using a thermocouple, and air flow rate is measured using a flowmeter. Materials are weighed and temperatures are measured every 300 s.

An experimental uncertainty analysis was also performed. The uncertainty was estimated using the following equation [44–46]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2} \quad (1)$$

The change in paddy mass is measured using a weighing scale. During each drying experiment, the mass of paddies was measured by removing it from the fluidized bed every 300 s.

The moisture content of paddy can be calculated by two methods on the basis of either dry or wet basis using the following equation.

The moisture content dry basis is calculated as [47]:

$$M(t) = \frac{M_h(t) - M_d}{M_d} \quad (2)$$

The moisture content wet basis is calculated as [47,7]: